NASA TM-84915

NASA-TM-84915 19840006054

NASA Technical Memorandum 84915
Revised January 1984

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August 1983

NASA
National Aeronautics and
Space Administration

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N84-14122#

THE USE OF OIL FOR IN-FLIGHT FLOW VISUALIZATON

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Abstract

Oil has been used to visualize in-flight aerodynamic characteristics such as boundary-layer transition, shock-wave location, regions of separated flow, and surface flow direction. The technique, which is similar to wind-tunnel oil-flow testing, involves applying an oil mixture to the test aircraft before takeoff. After takeoff, the airplane climbs immediately to the test altitude and photographs are taken. Although this was a limited study, NASA has gained considerable experience with the technique under widely varying flight conditions. Some of this flight testing was conducted specifically to develop the capabilities and versatility of the in-flight oil-flow technique, and there was some supplemental laboratory testing. This developmental experience is summarized, several examples of in-flight oil-flow photographs are presented and discussed, and an approach for potential users of the technique is recommended.

Introduction

Flow visualization is a very useful supplement to other fluid mechanics analytical techniques, such as pressure distribution measurements, and theoretical studies. Being able to see the flow characteristics can help determine, for example, where shock waves occur and whether flows are laminar, turbulent, or separated. Certain in-flight flow-visualization techniques have been developed, including the use tufts,[1] sublimation of chemicals,[2] and oil.

Since the summer of 1980, NASA's Dryden Flight Research Facility (DFRF) has conducted some limited tests on a variety of aircraft using oil for in-flight flow visualization. In these tests, an oil mixture is applied to the test aircraft just before takeoff and the aircraft climbs immediately to the test conditions; photographs of the flow patterns are taken, either from a chase aircraft or with a camera aboard the test aircraft.

An F-111 transonic aircraft technology (TACT) aircraft, which had a portion of the wing fitted with a natural laminar-flow airfoil section, was used in the first in-flight oil-flow study at Dryden. In that study, photographs of oil-flow patterns were compared, in terms of shock and boundary-layer characteristics, with results of pressure distribution and boundary-layer measurements. The results of that comparison showed that shock location and surface boundary-layer characteristics could be correctly identified from oil-flow photographs. Subsequently, oil-flow studies have been conducted on other airplanes operating at a variety of speeds and altitudes. As a result of the experience gained, the oil mixtures used and the test procedures have been refined, and the applicability and flexibility of the technique have been expanded.

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The primary purpose of this paper is to discuss the design of the test plan and various operational aspects of this in-flight visualization technique. Limited details of laboratory and flight development tests and a recommended approach for potential users are included, and examples of aerodynamic characteristics observed in oil-flow photographs are discussed.

Description of Test Aircraft

The seven aircraft on which oil-flow studies were conducted, as well as the oil-flow test sections on each, are shown in Fig. 1. Physical characteristics and specific information on the PIK-20E motor glider, F-14 fighter, and T-38 supersonic trainer are given in Ref. 3. The other aircraft shown in Fig. 1 were either designed or modified for flight research purposes; they are discussed briefly below.

F-111 TACT/NLF

A natural laminar flow (NLF) supercritical airfoil was fitted over a portion of the wing panels of the F-111 TACT aircraft, which is described in Ref. 4. The NLF sections were constructed using a fiberglass/foam sandwich technique described in Ref. 5. The spanwise width of the NLF airfoil sections was 1.83 m (6 ft) on both the left and right wings.

AD-1

The AD-1 is a low-speed, oblique-wing research vehicle.[6] It has a high-aspect-ratio oblique wing which can be pivoted from 0° to 60° sweep. The airplane has a high-fineness ratio fuselage, twin turbojet engines mounted on the fuselage aft of the wing, fixed gear, and is constructed with a fiberglass-reinforced sandwich separated by a core of rigid foam.

DAST

The drone for aerostructural testing (DAST) is a modified Firebee II drone; it is described in Ref. 7. The primary external modification to the Firebee II configuration is the substitution of a high-aspect-ratio, highly swept wing planform with a supercritical airfoil section for the basic wing. The DAST wing was constructed of fiberglass.

F-104/FTF

A vertical fin, referred to as the flight test fixture (FTF), was mounted on the lower centerline of a F-104 single-seat fighter. The fixture is used for local aerodynamic experiments at high speeds. This configuration is referred to as the F-104/FTF and it is described in more detail in Ref. 8. The results presented in this report were obtained with the leading edge of the fin modified with a laminar-flow airfoil, which was constructed using a fiberglass/foam sandwich technique.

Test Procedures and Conditions

Laboratory Tests

A ground-based environmental chamber was used to compare the flow rate of six oils at low temperatures. In each test, four oil samples were put in glass tubes, which were held vertically and plugged at each end. The samples were cold-soaked to a predetermined temperature in the environmental chamber. The four tubes were then inverted without opening the chamber and the relative flow rate of each sample was recorded. The test setup is shown in Fig. 2.

Flight Tests

The flight-test procedures were generally the same for all the experiments discussed in this report. Significant deviations from the following procedure are noted in the section entitled Discussion of Results.

The aircraft surface to be investigated was prepared before testing by removing dirt and other substances that could affect the oil patterns. In some cases the surface was smoothed to remove discontinuities caused by rivet heads or skin joints. This was accomplished with automotive body-putty or fiberglass. To prevent oil from entering flush static-pressure orifices, the orifices were sometimes covered with tape. It should be noted, however, that air trapped in the line between the tape and the pressure transducer will expand at altitude and can damage the transducer. As a precaution, the orifice lines were disconnected during the flights described here. Also, boundary-layer trip strips were used in some experiments. The trip strips consisted of Carborundum grains bonded on the surface with a spray adhesive. The grain size used was determined by the method described in Ref. 9. In some instances, reference marks were drawn on the surface to aid in interpreting the photographs. These were typically drawn spanwise across the area of interest at known chord intervals with a wide felt-tip marker. The marks were made so as not to cause surface discontinuities.

The oil was mixed with a pigment and applied to the surface with a paintbrush, usually about 30 min before takeoff. The oils and pigments that were used are summarized in Table 1. After takeoff the aircraft was flown at test conditions for up to several minutes. Photographs were then taken, either from a chase aircraft or with a camera aboard the test aircraft. The test-flight envelope at which photographs were obtained is shown in Fig. 3.

Most of the flight tests in this study were conducted in pursuit of other research objectives; however, some flights were dedicated to the development of the oil-flow technique. On these developmental flights, different oil solutions were applied to different sections of the test aircraft so that performance of the oils could be directly compared under identical flight conditions.

Discussion of Results

The results from the developmental testing, along with photographic examples, are presented in this section. The photographs are typical of oil-flow patterns seen in flight and can be used an aid in interpreting future results. Finally, based on the experience gained from these flight tests, a recommended procedure for the potential user is summarized.

F-111 TACT/NLF

The first oil-flow flights in this study were conducted on the upper surface of the experimental airfoil portion of the F-111 TACT/NLF wing. For this study Chevron* 80W-90 gear oil was mixed with powdered black graphite in a ratio of four parts oil to one part graphite by volume. Flight observations of the mixture indicated that at altitudes above 7.6 km (25,000 ft) the oil mixture was no longer responsive to the flow field of the wing. This was likely the result of the lower temperatures at high altitude causing an increase in the viscosity of the oil mixture. Consequently, the oil-flow studies were conducted at an altitude of 7.6 km (25,000 ft).

Between takeoff and the time at which the first test condition was established, most of the oil near the wing leading edge was moved aft by the airflow. Sufficient oil remained on the wing leading edge, however, for boundary-layer transition identification during the first 30 min of flight; shock-wave location was observable during one hour of flight.

Interpretations of the oil-flow photographs, with regard to shock and boundary-layer characteristics, were compared with results obtained from pressure-distribution and boundary-layer measurements. The results of that comparison showed that shock and laminar-to-turbulent boundary-layer transition could be correctly identified from the photographs.

In addition to the shock and boundary-layer visualization, a deformation of the airfoil test section during flight was discovered in the oil pattern. The deformation occurred at the location of an underlying control surface structure. Figure 4 is a representative oil-flow photograph from the F-111 TACT/NLF study and shows both the structural deformation and a normal shock location.

Laboratory Tests

After the F-111 tests, an attempt to extend the upper altitude capability of the oil technique was made, including laboratory tests to identify a more suitable oil. Particular attention was given to synthetic or parasynthetic oils since the viscosity of these is generally less sensitive to temperature variation. High viscosity at the higher altitudes (low temperatures) typical of flight testing can result in poor response of the oil to the flow field. Furthermore, the lower oil viscosity encountered at lower altitudes (warmer temperatures) during takeoff and climbout can result in much of the oil being removed by the airflow.

The laboratory tests were intended to compare Chevron 80W-90 oil, the in-flight characteristics of which were known from the F-111 TACT/NLF tests, with other candidate oils. The results of these

*Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

laboratory tests are summarized in Fig. 5. The most interesting oils were the AMS Oil Gear Lube and Mobil 1, since they showed the least flow-rate variation with temperature change. The Mobil 1 flowed more rapidly than all other oils tested.

Other characteristics besides flow rate are of interest, however, such as coloration, surface properties, and density. Therefore, in-flight comparisons are the preferred method of evaluating the suitability of particular oils.

AD-1

The next set of flight tests was conducted on the AD-1 airplane. Based on the laboratory test results, oils were selected to document the flow characteristics. Also a different darkening agent, putty black (FeO_2), was used in an attempt to provide more contrast between the oil and wing surface. Observations, as well as photographs from a chase plane, were used to compare the usefulness of the oils and darkening agent.

On the first flight, four oils were applied to the wing in different regions. Mobil 1 was the most responsive to the flow conditions but was removed from the wing by the airflow early in the flight. The AMS/Oil Para-Synthetic Engine Oil (hereinafter AMS/Oil Para-Synthetic) was less responsive, but remained on the wing throughout the flight.

On the second flight, a mixture of equal parts of Mobil 1 and AMS/Oil Para-Synthetic was compared with Mobil 1. The mixture of Mobil 1 and AMS/Oil responded well to the flow conditions and remained on the wing. This mixture was therefore used on subsequent flights.

On two flights, the order of the flight-test points was reversed to investigate the repeatability of the oil-flow patterns. The test-point order had no observable effect on the oil patterns.

Also, a mixture ratio of the lamp black and oil was varied from 10 parts oil to 1 part putty black to 20 parts oil and 1 part putty black. The oil patterns showed little sensitivity to the mixture ratio; however, a ratio of 15 parts oil to 1 part putty black was necessary for good visualization.

On one flight, a boundary-layer trip strip was applied to the wing at 10% chord. The photographs obtained from this flight, in which the location of boundary-layer transition was known, proved useful in interpreting results from other flights. An example of this will be discussed with the PIK-20E results.

A photograph from the AD-1 oil-flow experiments is shown in Fig. 6. Boundary-layer transition on the left wing is assumed to occur at the line of contrast in the oil color which is indicated in the photograph. The random pattern of oil over portions of the left aileron is thought to be an indication of separated flow.

F-14

Three oil-flow flights were conducted using the F-14. Before the first flight, a portion of the left-wing leading-edge slat was smoothed, using automotive body-putty. Oil was applied to this region and tested at transonic speeds at altitudes at up to 7.6 km (25,000 ft). A smooth fiberglass faring was applied to a somewhat larger area of the leading edge for the next two flights in an attempt to extend the laminar boundary-layer region. The entire left wing was oiled for these flights. Trip strips were located at 10, 20, and 30% chord for one flight on small sections of fiberglass.

Because of time constraints it was not possible to conduct additional oil-mixture studies. There was a concern that the mixture of Mobil 1 and AMS/Oil Para-Synthetic might be too inviscid for this speed range, and, therefore, only the more viscid AMS/Oil Gear Lube was used in these tests.

The AMS/Oil gear lube was unresponsive to the flow conditions at an altitude of 7.6 km (25,000 ft). Good response was observed at this altitude during the F-111 TACT/NLF study. Unlike those tests, however, the F-14 flights were conducted in the winter, which resulted in lower atmospheric temperatures. Consequently, most of the F-14 tests were conducted at 6.1 km (20,000 ft).

In Fig. 7, the oil-flow pattern observed on the F-14 airplane in high-speed flight (0.84 Mach number) is shown. The line of oil denoted in the photograph appears to identify the transonic shock-wave location. At the time this photograph was taken, most of the oil had been removed by the airflow. Because of this, boundary-layer transition is not distinguishable, although the shock location is still visible. Many oil streaks can be seen in the photograph, some of which have been labeled. These emanate from surface discontinuities, such as the lap joint at the leading-edge slat where oil has been trapped. The fiberglass faring which was applied to a portion of the wing leading edge eliminated this problem.

The smoothed portions of the wing surface provided the best oil-flow visualization, since rivet and bolt heads, steps, and gaps had been faired over and did not cause streaking in the oil. The use of trip strips again provided a useful reference indication of boundary-layer transition. Transition and shock location were successfully identified from the tests.

During the F-14 oil-flow testing some oil became trapped in the wing flap and spoiler area, and could not be conveniently cleaned. Oil seeped out of these areas on subsequent flights. This was an annoyance to the aircraft maintenance crew due to the additional cleaning required.

DAST

Oil was applied to the upper and lower surfaces of the left wing of the DAST vehicle. The DAST was carried aloft under the right wing of a B-52. On this flight it was not released from the B-52 and the oil-flow tests were conducted while the DAST was mated to the B-52. Of particular interest for this oil-flow experiment was that the wing of the DAST is black and therefore a white pigment was used in the oil to enhance contrast. The oil pattern was photographed at Mach 0.4 at an altitude of 5.5 km (18,000 ft).

A photograph of the DAST oil-flow test is shown in Fig. 8. The contrast between the oil and surface is satisfactory for flow visualization. On

examining the wing surface after flight, the resulting oil pattern appeared to indicate the streamlines of the airflow at the surface. This characteristic has not been observed when using putty black as the oil pigment. The usefulness of this pigment for identifying shock waves or transition has not been verified.

F-104/FTF

AMS/Oil Gear Lube and the mixture of Mobil 1 and AMS/Oil Para-Synthetic were compared in flight on the F-104/FTF. The two solutions, mixed with putty black, were painted on opposite sides of the vertical flight test fixture just before takeoff. Trip strips were attached to sections on each side of the test fixture, and tape was placed over existing flush static pressure orifices. Tests were conducted over a wide speed range from Mach 0.6 to 1.25 at altitudes up to 7.1 km (23,000 ft).

The oil-flow experiment on the F-104/FTF was the only attempt at obtaining oil-flow patterns on a vertical surface. Of the two oil solutions which were compared, the mixture of AMS/Oil Para-Synthetic and Mobil 1 was the best for test purposes. Photographs were taken soon after takeoff at which time most of the AMS/Oil Gear Lube was gone. Although both solutions were applied at approximately the same time, it is possible that more of the AMS/Oil Gear Lube ran off the vertical fin before takeoff. The mixture provided good visualization of boundary-layer transition and shock-wave location at the flight-test conditions.

An oil-flow pattern on the F-104/FTF is shown in Fig. 9 at an altitude of 7.0 km (23,000 ft) and Mach 1.2. Because of the high dynamic pressure, much of the oil had been removed from the surface by the time this photograph was taken; therefore, boundary-layer transition is not visible. The location of an oblique shock wave is visible, however, as noted in the figure.

PIK-20E

Low-speed oil-flow visualization flights were were conducted on the PIK-20E motor-glider. On the first two flights, four oil solutions were compared. On the next two flights only the mixture of AMS/Oil Para-Synthetic Engine Oil and Mobil 1 was used to obtain a detailed flow survey of part of the upper surface. Trip strips were used, and the flight conditions were repeated in reverse order during the testing.

Of the four oil solutions tested on the first two flights (Mobil 1, Pennzoil 10-40W, AMS/Oil gear lube, and the mixture of AMS/Oil Para-Synthetic Engine Oil and Mobil 1), the mixture was the most responsive to the aerodynamic flow field. At the low airspeeds encountered, sufficient quantities of all four solutions remained on the wing throughout the flight (about 30 min). In the time-sequence photographs shown in Fig. 10, the flight conditions changed from near stall to higher airspeeds (Fig. 10(a) to Fig. 10(c)). As noted in Fig. 10, the first change in the oil-flow patterns is seen in the mixture of AMS/Oil Para-Synthetic and Mobil 1. This mixture was successfully used in later flights to determine the location of boundary-layer transition as a function of airspeed.

The oil-flow patterns generally were repeated when the order of the flight test conditions was reversed, although in some cases, "ghost" images from previous conditions were visible. The use of trip strips on some flights was again useful for interpreting the boundary-layer characteristics.

In Fig. 11(a), the location of natural boundary-layer transition on the PIK-20E is denoted by an arrow. Reference marks were painted on the wing at 10% and 20% chord stations. On the outboard section of the oil, a trip strip was applied at the 40% chord location. The contrast in oil color across the trip strip is the same as the contrast that occurs at natural transition. At about the midspan of the oiled test section, a transition wedge (presumably caused by a surface blemish) is noted. Aft of the natural transition line, a sharply defined spanwise line can be seen. This line occurs at the location of an interior structural element. It is interesting to note that this distinct line is not present at the span stations where forced transition occurred. Post-flight inspection of the surface revealed no waviness or discontinuity at the location; however, flight loads which might distort the surface in flight were not simulated. Fig. 11(a) shows the pattern at 60 KIAS. At a higher airspeed (Fig. 11(b)), natural transition is shown to occur slightly farther aft, close to the location of the structural member. The buildup of oil at this location is sufficient that several streaks of oil have emerged from the pooling.

T-38

Two research flights of the T-38 were used to compare four different oil solutions at high speeds and altitudes, as well as to investigate the response of the oil-flow patterns to a dynamic flow field. On the first flight, four different oil solutions were painted on separate regions of the upper surface of the right and left wing. The flight plan consisted of accelerating from subsonic to transonic speeds at several altitudes up to 14 km (45,000 ft). The lowest atmospheric temperature encountered was about -60°C. The mixture of AMS/Oil Para-Synthetic and Mobil 1 was applied to the upper surface of the left wing for the second flight. The flight plan consisted of wing-rock maneuvers at 0.9 Mach number and low-speed wing rock in 1-g flight. Photographs were made from the rear cockpit of the T-38.

An example of the photographs taken of the T-38 flight tests is shown in Fig. 12. On the right wing (Fig. 12(a)), it is seen that most of the Mobil 1 and Exxon Synesstic 32 has been removed from the surface, indicating they are not suitable for flow visualization at these speeds. On the left wing (Fig. 12(b)), the dark line denoting shock-wave location is evident in the mixture of AMS/Oil Para-Synthetic and Mobil 1. Unfortunately, the AMS/Oil gear lube oil pattern is greatly affected by local turbulence near rivet heads and the flap hinge, and, therefore, a fair comparison between the two solutions on the left wing was not possible.

The mixture of AMS/Oil Para-Synthetic and Mobil 1 responded well to the flow field at altitudes up to 6.1 km (20,000 ft). Weather balloon

data indicated that the temperature at that altitude was about -22.5°C during the testing. At higher altitudes some variation in the oil pattern can be seen as a function of flight conditions; however, it is much less conclusive. Holding flight conditions longer at the higher altitudes might improve the results.

Recommended Approach

The recommendations presented below are based on limited laboratory and flight experience gained to date. The technique has been refined (but not optimized) and can be expected to yield satisfactory results. This approach includes surface preparation, flight planning, and postflight considerations.

Smooth surfaces such as those of fiberglass, which have no skin joints or rivet heads, generally give better results since local aerodynamic turbulence near discontinuities makes the oil patterns difficult to interpret. Smoothing over depressions in the skin using fiberglass or putty will improve the results.

The surface finish should also be inspected for grease or other substances which might affect the oil-flow pattern.

For boundary-layer-transition visualization, a "trip strip" is often recommended for a portion of the test section to provide a region of known transition. This can be used as a reference point and as an aid in interpreting the oil pattern. Also, identification marks located at known chord or span locations are useful in analyzing photographs.

The oil mixture can be applied with a paintbrush to the surface of interest just before takeoff. A mixture of AMS/Oil Para-Synthetic and Mobil 1 was the most successful solution tested. The two oils are mixed in a 1:1 ratio and combined with a pigment to provide a contrast with the surface. When applied to white or aluminum surfaces, ferric oxide (FeO_2), which is commercially available as putty black from crafts or art supply stores, is used as a black pigment. One part FeO_2 is mixed with 10 to 15 parts of the oil mixture. A white pigment, titanium dioxide (TiO_2), can be used to enhance the contrast with dark surfaces. Titanium dioxide should be mixed with oil in about a 1:1 ratio. It is important to avoid clumps of undissolved pigment in the solution since this can result in premature boundary-layer transition. This problem can be avoided by first mixing a small amount of oil with the pigment to form a smooth thick paste and then adding the remaining oil.

Since large dirt particles can easily stick in the oil film causing premature boundary-layer transition, the oil should be applied just before takeoff; taxiing airplanes and other sources of dirt and dust should be avoided.

When designing flight plans it is important to keep in mind the physical mechanics of the oil-flow technique in order to obtain satisfactory photographs. The effects of temperature at altitude and dynamic pressure must be considered to insure that the resulting oil pattern is an accurate representation of the flow field.

At low atmospheric temperatures encountered at high altitudes, the oil is less responsive to the airflow. Therefore, the desired flight conditions must be maintained longer to insure that the oil pattern has adapted to the flow field. Good results have been obtained at altitudes up to 7.6 km (25,000 ft) after 60 sec at the test-flight conditions. Tests at higher altitudes have been less successful although holding test conditions for longer periods (longer than 60 sec) has not been tried. The use of a less viscous oil may improve the results; however, in order to reach high altitudes, aircraft generally encounter high dynamic pressures which would remove thinner (less viscous) oils.

In low-speed flight (dynamic pressures less than 100 lb/ft^2), enough oil is left on the surface to identify transition and separation for at least 30 min of flight time. Observations should first be made at those flight conditions at which transition is expected to occur at the aftmost position. Turbulent and separated flows remove oil from the surface more rapidly, and, as oil is lost, less contrast will be seen in the remaining oil film.

In low-speed flight, maintaining flight conditions for 60 sec appears to be sufficient to ensure that the oil has responded to the current flow field. This can be verified by repeating certain test points at various times during the same flight and checking that the results are identical. If a very prominent flow condition occurs at one flight condition, it may remain in the oil as a "ghost" pattern and interfere with later results. It is, therefore, helpful to record the time sequence in which the photographs are taken.

At higher airspeeds, much less oil is left on the surface. Although the dynamic pressure on the oil is higher, the oil film is much thinner and too sparse to rearrange in grossly different flow patterns on a single flight. As noted earlier, at least 60 sec should be spent at test conditions to ensure that the flow field has been represented. If prominent flow conditions, such as transition wedges or shock waves, are present throughout a significant portion of a flight, indications will remain in the oil pattern even after landing.

Boundary-layer transition is visible in oil patterns during high-speed flight (Mach numbers above 0.6), but observations should be made within 30 min of takeoff. Because oil is lost from the leading edge during flight, transition is more difficult to distinguish near the leading edge. Visualization of the location of shock-waves requires less oil and is, therefore, possible after longer periods of flight time.

The most commonly encountered operational problems involved obtaining high-quality, in-flight photographs. When possible, on-board photography is best. By necessity, however, most of the pictures shown in this report were taken from chase planes. Typically, large format film (2-1/2 in square frame) and a 150 mm lens were used. Direct sunlight is necessary for good contrast and so that fast shutter speeds can be used.

After testing, most of the excess oil can be wiped off. Engine degreaser or solvent is used to clean the remaining surface film. Some parts of the oiled surfaces (e.g., flap hinges) obviously cannot be easily cleaned without disassembly; how-

ever, the problem does not ordinarily interfere with aircraft operation. The effect of the oil or cleaning solution on unusual surface materials or adhesive bonds should be considered, however, for flight safety purposes.

Analysis of in-flight oil-flow photographs must be conducted on a case-by-case basis in order to insure valid conclusions. Besides the aerodynamic characteristics that are of interest, misleading features are also revealed in the oil-flow pattern. For example, the location of underlying structural elements can often be observed in the oil pattern. Also, if oil builds up or pools in a certain location owing to local separation or surface discontinuity it may suddenly streak downstream. Furthermore, a hysteresis in the oil pattern may occur between flight conditions.

Clearly, some features observed in the oil-flow photographs are not well understood. Careful analysis of the photographs, as well as a knowledge of the oil-flow test setup and flight profile, is necessary to interpret the aerodynamic characteristics accurately.

Concluding Remarks

The oil-flow technique is a useful tool for in-flight, steady-state flow visualization. It is possible to locate boundary-layer transition, regions of separated flow, and shock-wave position under a wide variety of flight conditions using this technique. The technique is simple, requires no significant vehicle modification, and is inexpensive. Moreover, oil-flow testing is a passive process and can be performed in conjunction with other flight experiments. High-quality in-flight photography is typically the most demanding requirement.

Based on some developmental testing at the Dryden Flight Research Facility, a recommended approach for users has been described. This includes specific information about the oils used, application techniques, and flight planning. As a result of comparative flight testing it was shown that certain oil mixtures enhance the results.

Further optimization of this visualization technique will occur as more experience is obtained. To make sure that valid conclusions are drawn, oil-flow photographs must be analyzed carefully. The oil-flow patterns have many characteristics which are not well understood and which can be misinterpreted. Confidence in the results can be increased by designing flight plans so that test conditions are repeated, by using trip strips and by smoothing test surfaces.

The process has not yet been optimized, and there are some features that are not fully understood; nevertheless, the test technique has been successful. Because of the simplicity of the technique it is an attractive in-flight aerodynamic analytical tool. Significant improvements in the method have already been made based on the work accomplished to date, and further improvements can be expected as more experience is gained.

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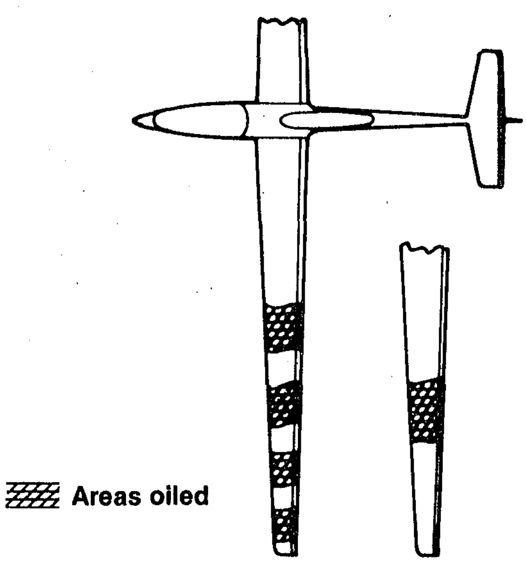
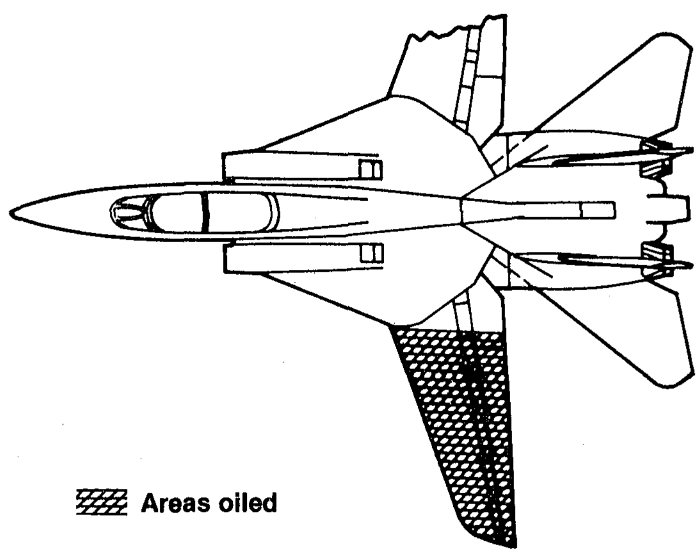
Table 1 Summary of flight experiments.

Aircraft	Flight-test period	Number of flights	Oil solutions tested	Pigment
F-111 TACT/NLF	Aug. 1980	4	Chevron 80W-90	Graphite
AD-1	May-June, 1982	5	AMS/Oil Synthetic Gear Lube (EP) AMS/Oil Para-Synthetic Engine Oil Chevron 80W-90 Mobil 1 Mixture[a]	FeO_2
F-14	Jan. 1983	3	AMS/Oil Synthetic Gear Lube (EP)	FeO_2
DAST	Feb. 1983	1	AMS/Oil Synthetic Gear Lube (EP)	TiO_2
F-104/FTF	Mar. 1983	1	AMS/Oil Synthetic Gear Lube (EP) Mixture[a]	FeO_2
PIK-20E	Apr. 1983	4	AMS/Oil Synthetic Gear Lube (EP) Mobil 1 Mixture[a] Pennzoil (10-40W)	FeO_2
T-38	May 1983	2	Exxon Synesstic 32 Mixture[a] AMS/Oil Synthetic Gear Lube (EP) Mobil 1	FeO_2

[a]Mixture of AMS/Oil Para-Synthetic Engine Oil and Mobil (1:1).

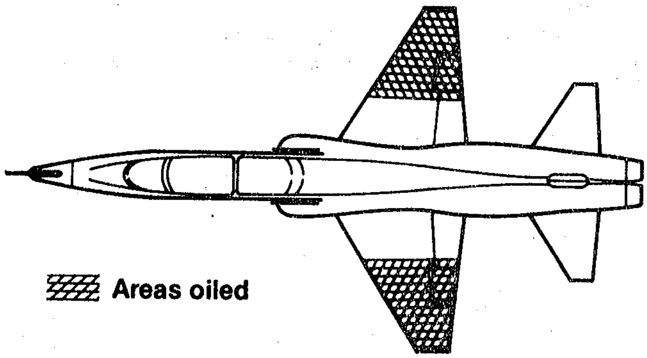


(a) PIK-20E.

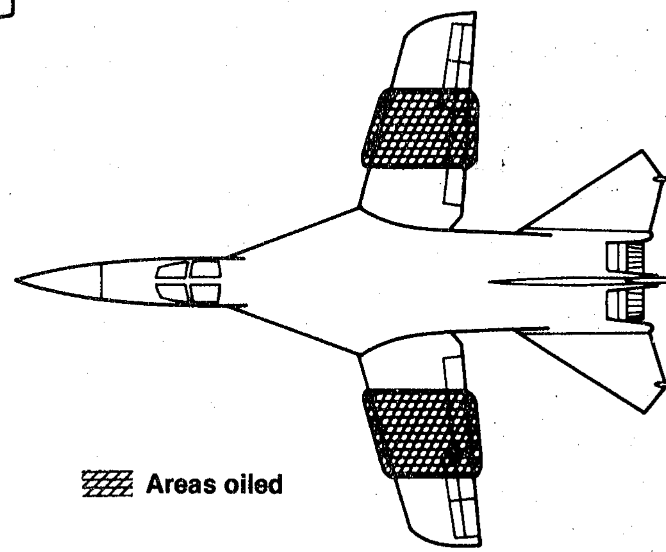


(b) F-14.

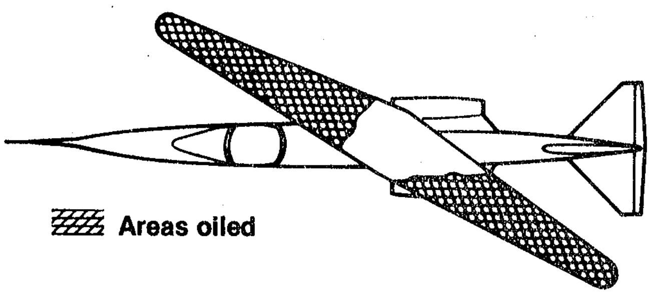
Fig. 1 Aircraft used and oil-flow test sections.



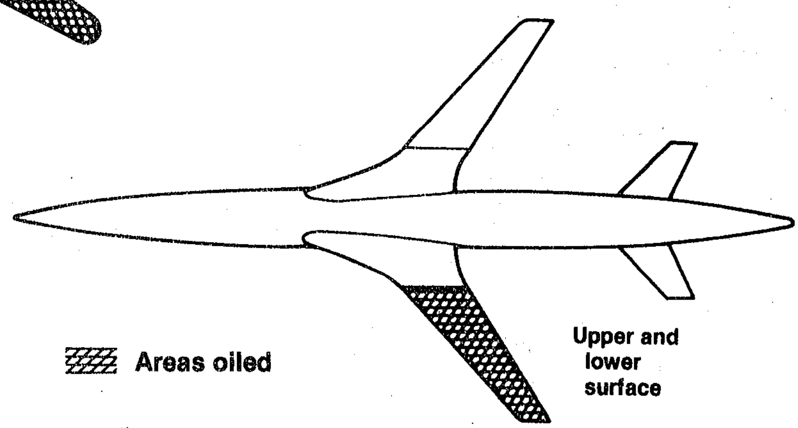
(c) T-38.



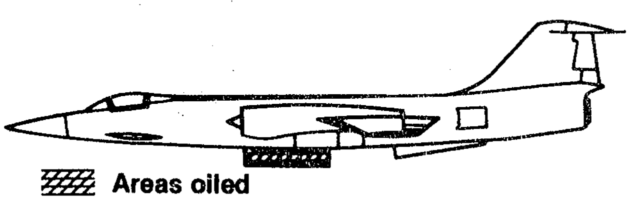
(d) F-111/NLF.



(e) AD-1.



(f) DAST.



(g) F-104/FTF.

Fig. 1 Concluded.

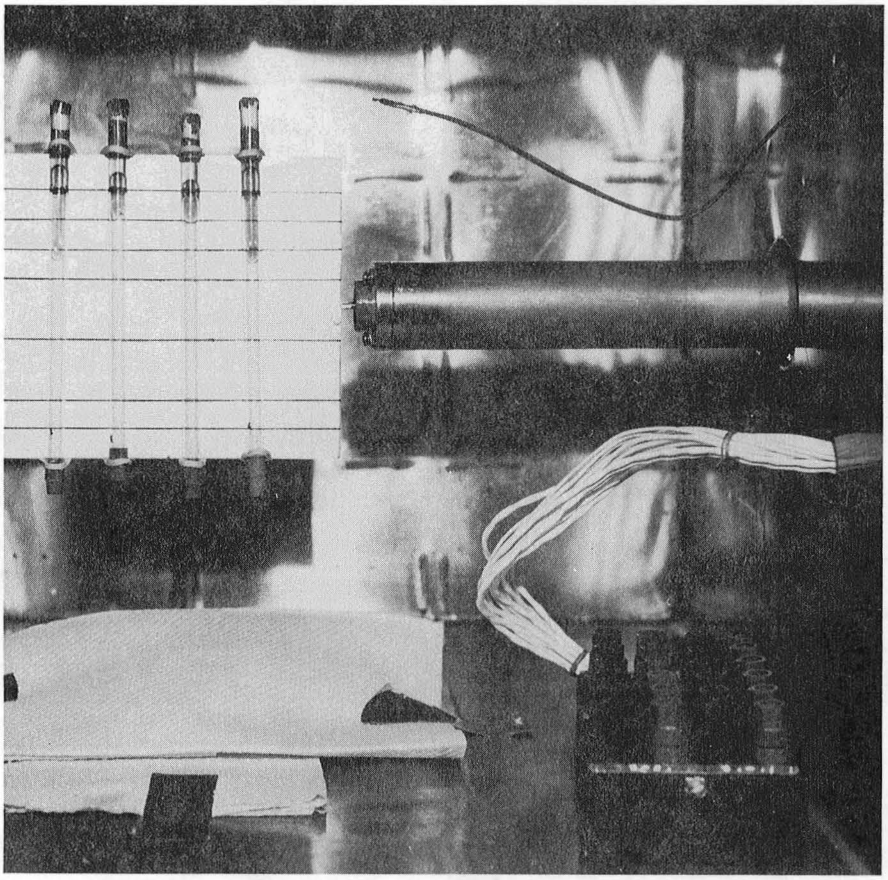


Fig. 2 Laboratory test setup.

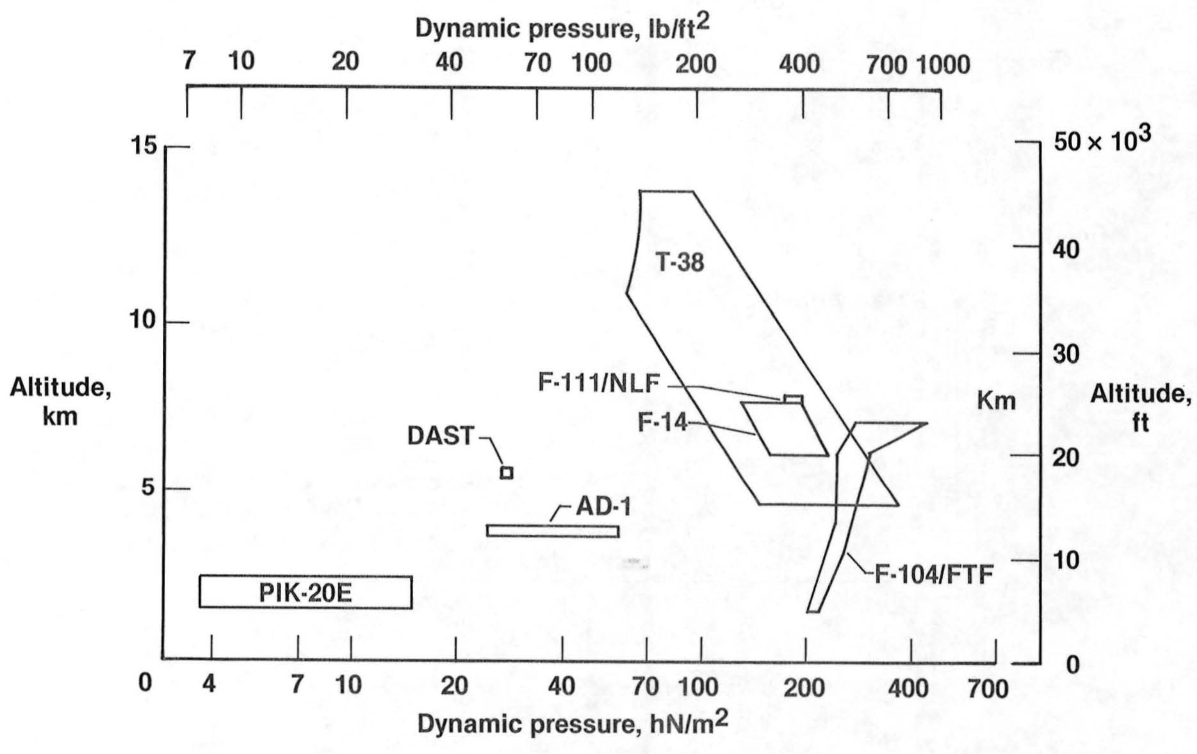


Fig. 3 Flight conditions at which oil-flow patterns were photographed.

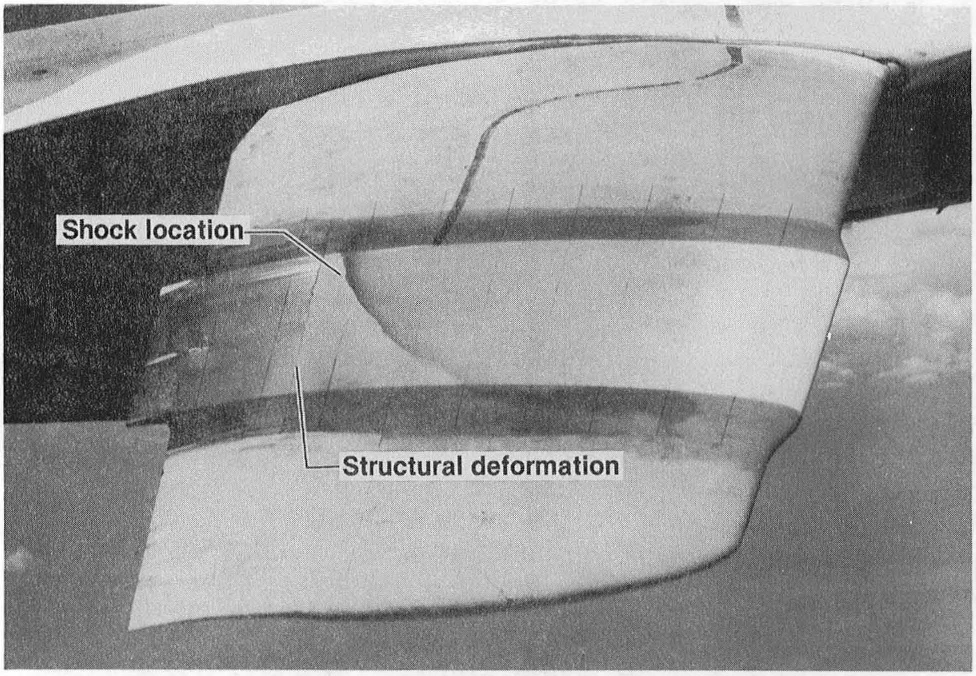


Fig. 4 F-111 TACT/NLF oil-flow experiment: Mach 0.85, 26° wing sweep, altitude 7.6 km (25,000 ft).

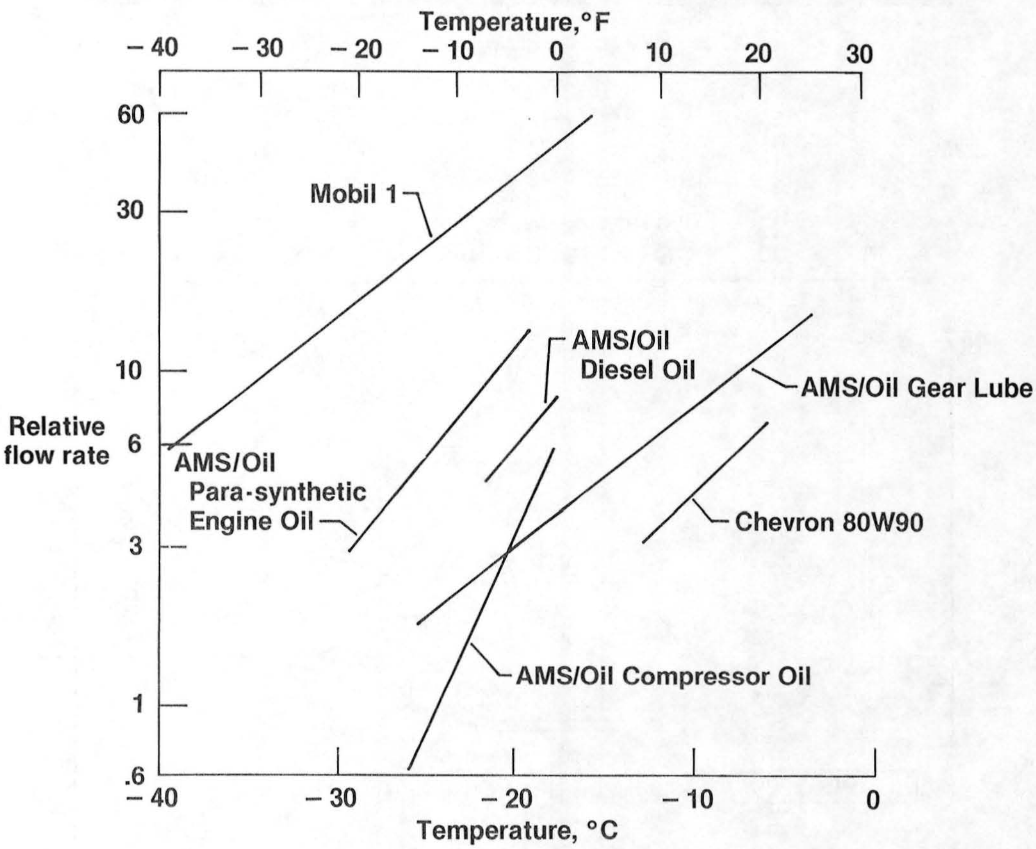


Fig. 5 Experimental oil-flow rate data.

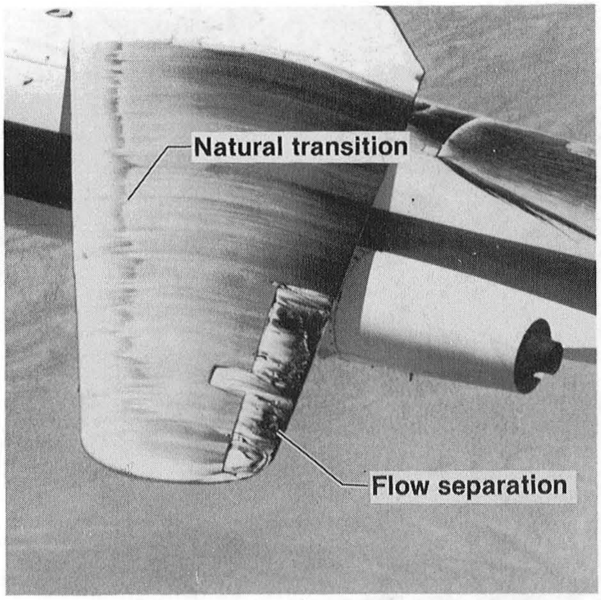


Fig. 6 AD-1 oil-flow experiment: Indicated airspeed 45.3 m/sec (87.9 knots), 30° wing sweep.

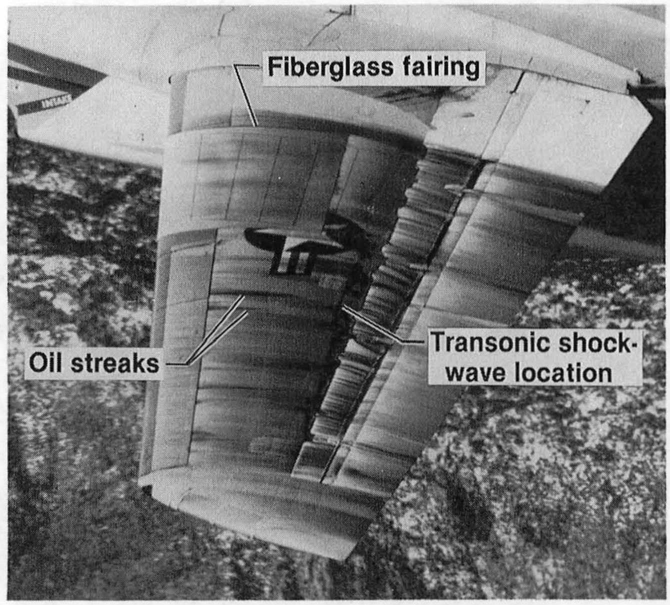


Fig. 7 F-14 oil-flow experiment: Mach 0.84, 20° wing sweep, altitude 6.1 km (20,000 ft).

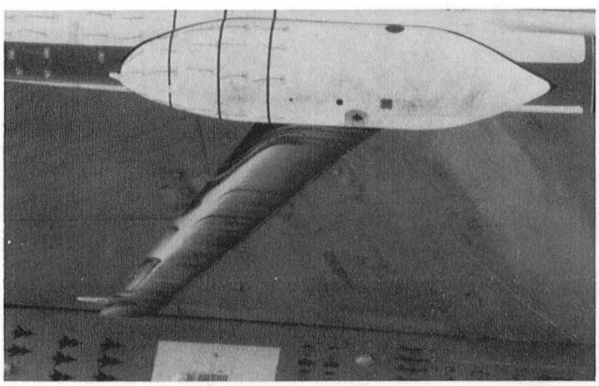


Fig. 8 DAST oil-flow testing using white pigment.

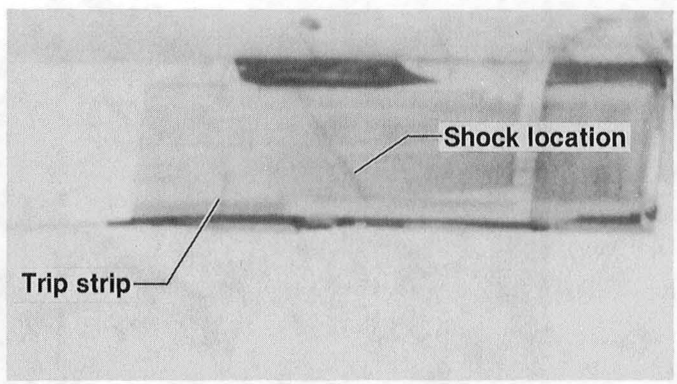
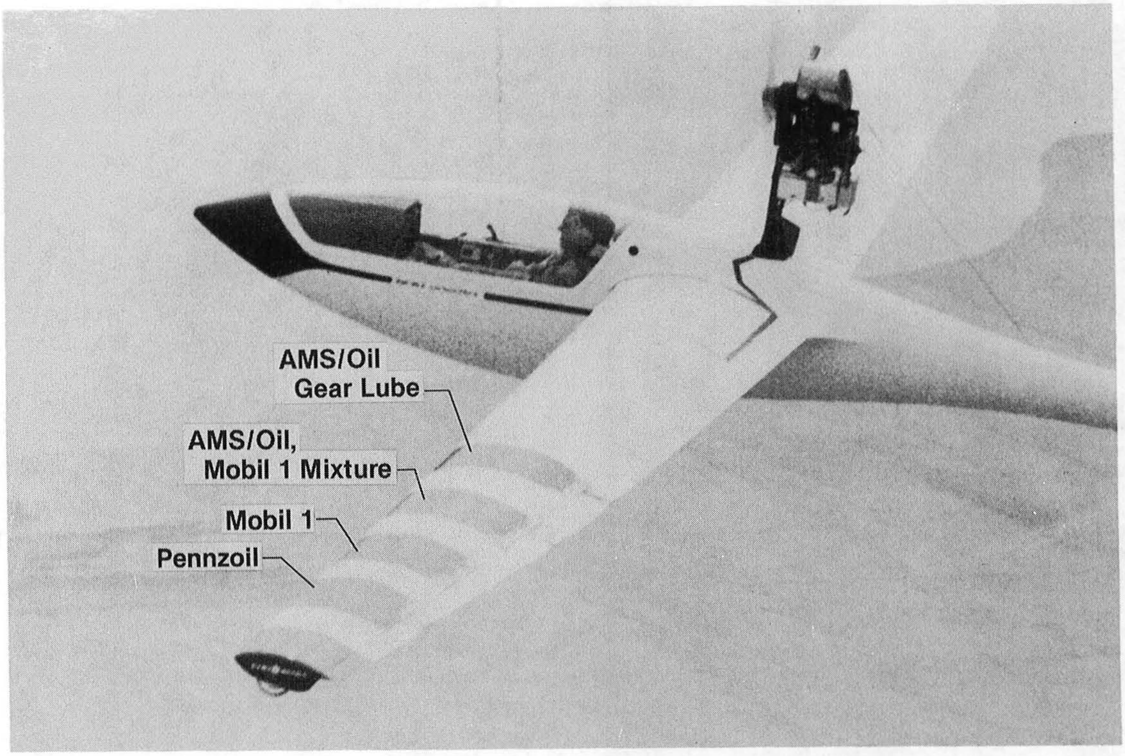
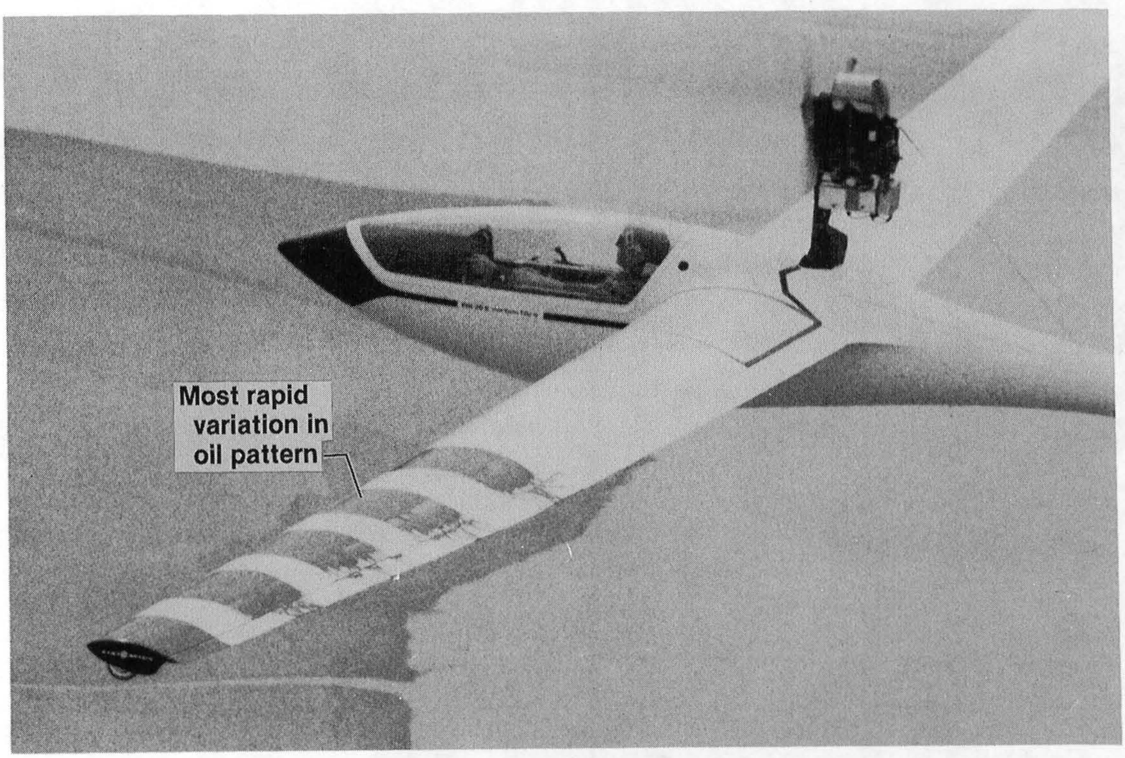


Fig. 9 F-104/FTF oil-flow experiment: Mach 1.2, altitude 7.0 km (23,000 ft).

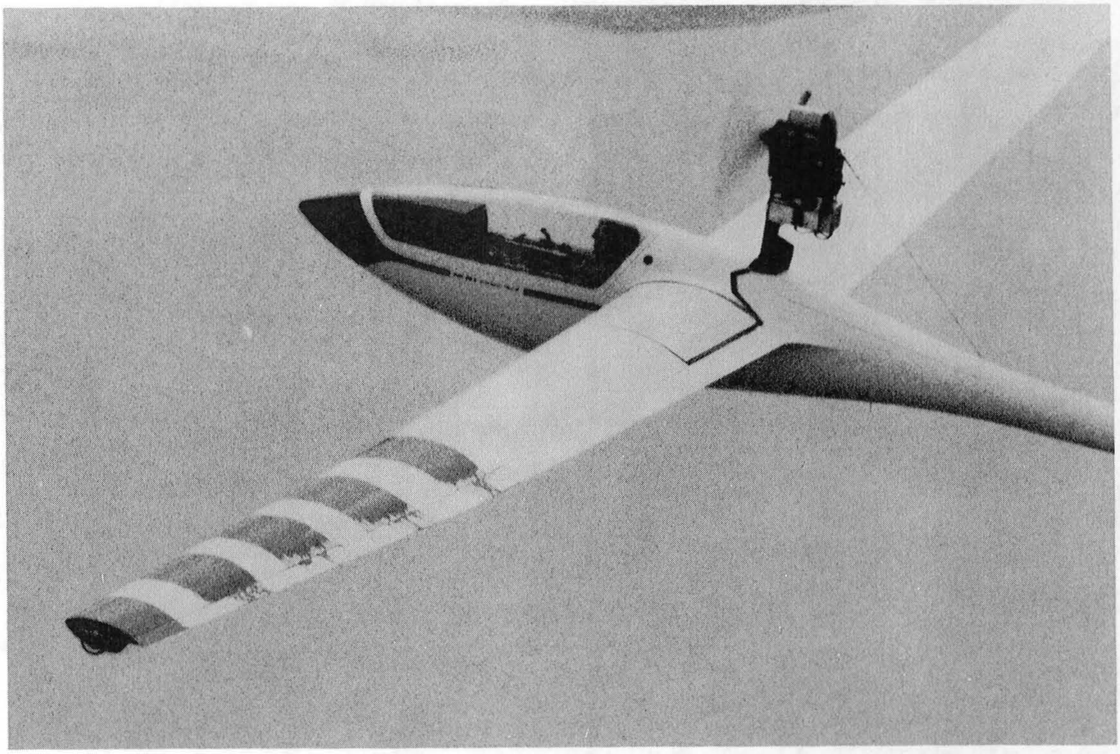


(a) Indicated airspeed 23.2 m/sec (45 knots).



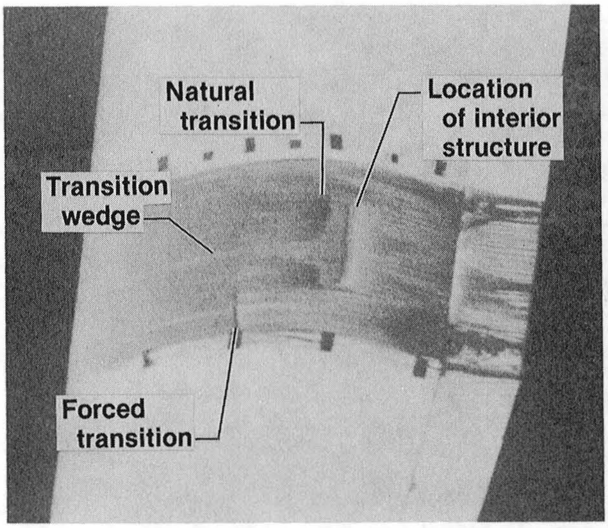
(b) Indicated airspeed 25.7 m/sec (50 knots).

Fig. 10 Time-sequence of PIK-20E oil-flow experiment at increasing airspeeds.

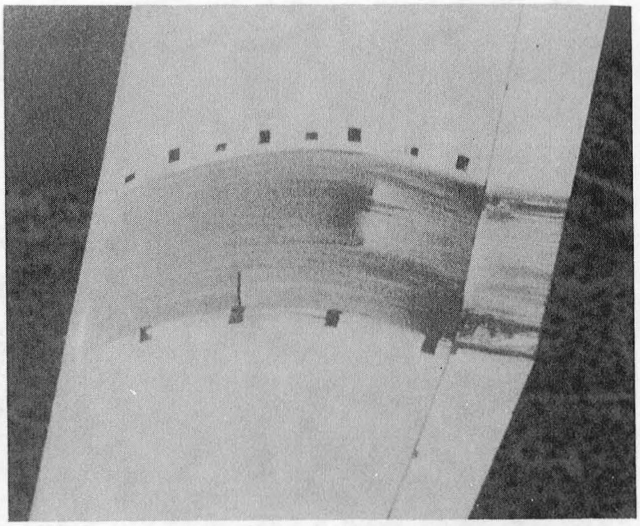


(c) Indicated airspeed 30.9 m/sec (60 knots).

Fig. 10 Concluded.

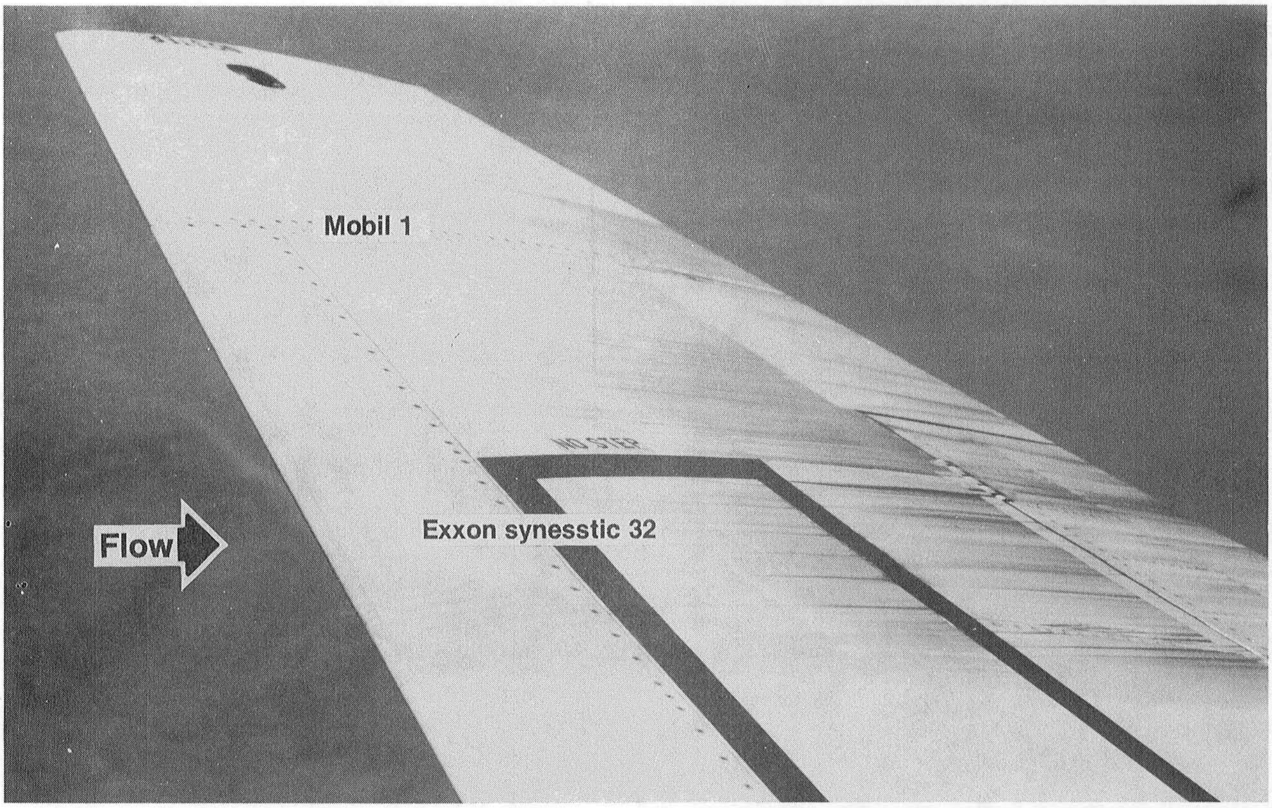


(a) Indicated airspeed 30.9 m/sec (60 knots).

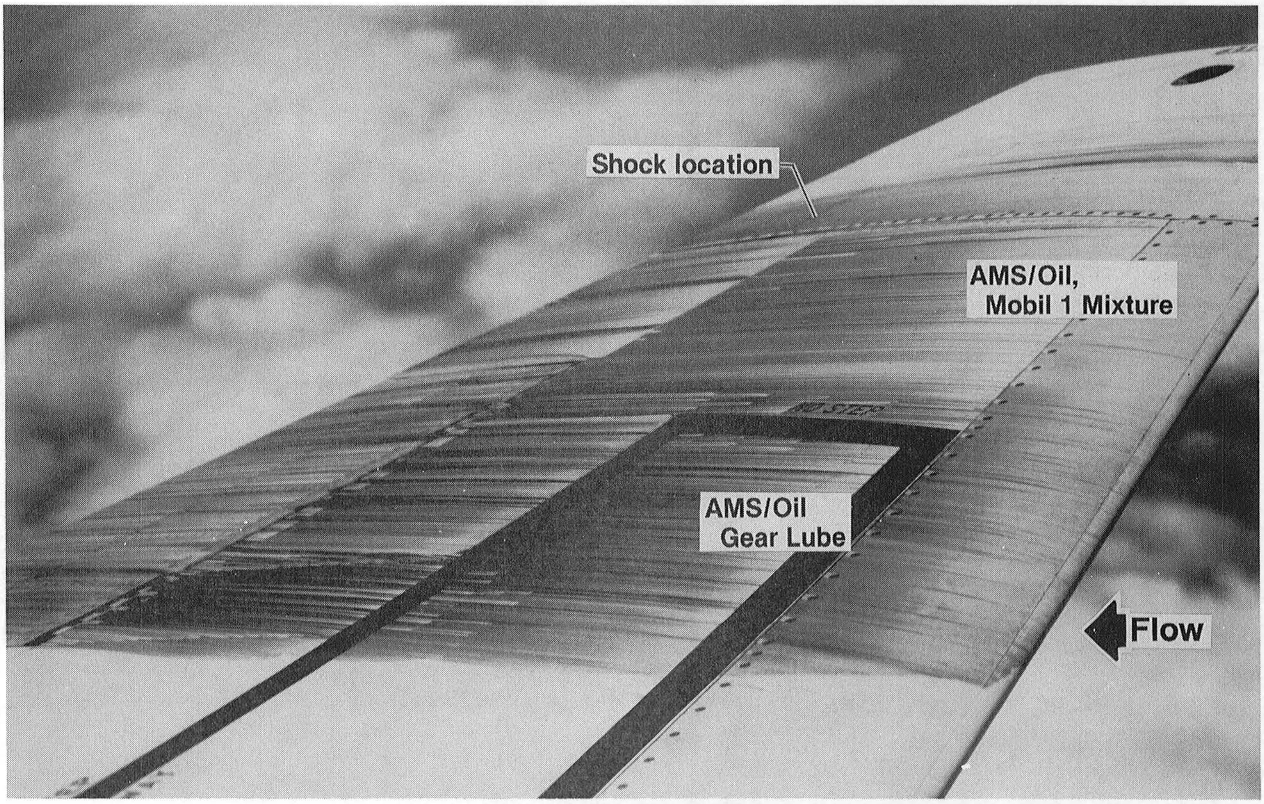


(b) Indicated airspeed 48.9 m/sec (95 knots).

Fig. 11 PIK-20E oil-flow experiment.



(a) Right wing.



(b) Left wing.

Fig. 12 T-38 oil-flow experiments: Mach 0.95, altitude 7.6 km (25,000 ft).

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-84915, Rev. Jan. 1984		
4. Title and Subtitle THE USE OF OIL FOR IN-FLIGHT FLOW VISUALIZATION		5. Report Date August 1983 6. Performing Organization Code
7. Author(s) Robert E. Curry, Robert R. Meyer, Jr., and Maureen O'Connor		8. Performing Organization Report No. H-1195
9. Performing Organization Name and Address NASA Ames Research Center Dryden Flight Research Facility P.O. Box 273 Edwards, California 93523		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code RTOP 505-31-21

15. Supplementary Notes

This paper was presented at the 14th Annual Symposium of the Society of Flight Test Engineers, Newport Beach, California, August 15-19, 1983.

16. Abstract

Oil has been used to visualize in-flight aerodynamic characteristics such as boundary-layer transition, shock-wave location, regions of separated flow, and surface flow direction. The technique, which is similar to wind-tunnel oil-flow testing, involves applying an oil mixture to the test aircraft before takeoff. After takeoff, the airplane climbs immediately to the test altitude and photographs are taken. Although this was a limited study, NASA has gained considerable experience with the technique under widely varying flight conditions. Some of this flight testing was conducted specifically to develop the capabilities and versatility of the in-flight oil-flow technique, and there was some supplemental laboratory testing. This developmental experience is summarized, several examples of in-flight oil-flow photographs are presented and discussed, and an approach for potential users of the technique is recommended.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Flow visualization Shock location Boundary-layer transition Separated flow	Unclassified-Unlimited STAR category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	16	A02

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